

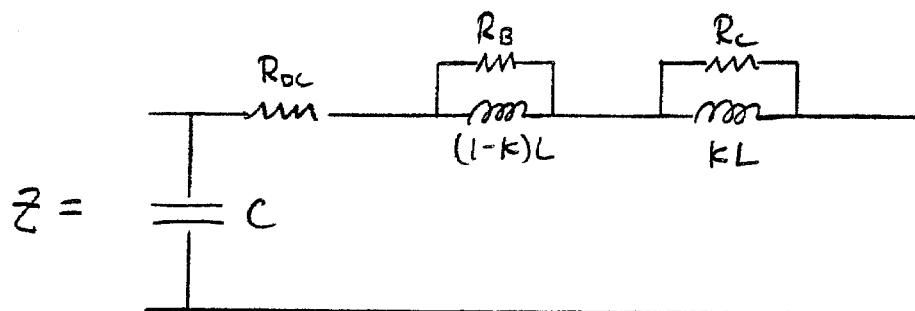
# Interpretation of Inductance Bridge Measurements of E. D. Dipoles

R. Shafer

In order to make electrical quality-control checks on the ED magnets, simple AC inductance bridge measurements are necessary. Although these measurements are nowhere near the completeness of the magnetic field and AC loss measurements, they can be performed in a few minutes on a warm magnet, and provide information which is not obtainable by DC measurements (leakage currents and DC resistance). The purpose of this note is to discuss the usefulness of these measurements as a QC check, and how to interpret them.

## Model

Impedance measurements over a wide range of frequencies (10Hz-5kHz) show that the equivalent electrical circuit of the dipole coil, including eddy current losses, is



where  $L = 49\text{mH}$  (dc inductance)

$k = 0.6$  (coupling to eddy current losses in cryostat)

$R_C = 50$  ohms equivalent eddy current load of cryostat

$R_B = 350$  ohms equivalent eddy current load of bore tube

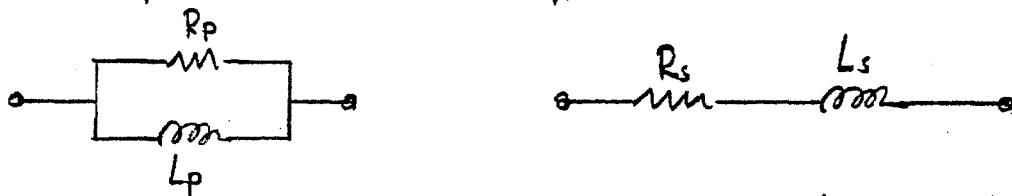
$R_{DC} = 4.8$  ohms DC resistance of warm coil

C ~ 30nF      inter-turn capacitance of coil (set to zero in tests below)

All of the above parameters are likely to vary somewhat from magnet to magnet and/or with temperature, and/or with various ways of grounding the cryostat and collars.

### Bridge Measurements.

Inductance bridge measurements assume an equivalent circuit either of the parallel or series type:



where  $Q_p = \frac{R_p}{\omega L_p}$        $Q_s = \frac{\omega L_s}{R_s}$        $Q_s = Q_p$

It is important to note that the  $Q$  of the circuit has the same value for the two models i.e. it is model independent.

Also the impedance (real and imaginary components) of the circuit at any frequency is model independent, leading to the relations:

$$R_p = (1+Q^2) R_s$$

$$L_p = \frac{(1+Q^2)}{Q^2} L_s$$

We wish to examine both these models to determine which one is more likely to see QC problems in a magnet, and perhaps to select a frequency at which QC problems are

most obvious.

The following table presents typical values of  $R_s$ ,  $L_s$ ,  $Q_s$ ,  $R_p$ ,  $L_p$ , and  $Q_p$  for a dipole, based on the above model.

F(Hz)	$R_s$	$L_s$	$Q_s$	$R_p$	$L_p$	$Q_p$
10.	4.86	48.97	0.63	6.81	171.06	0.63
15.	4.93	48.94	0.94	9.25	104.88	0.94
20.	5.03	48.89	1.22	12.53	81.70	1.22
30.	5.32	48.75	1.73	21.19	65.10	1.73
50.	6.23	48.32	2.44	43.23	56.45	2.44
70.	7.54	47.69	2.78	65.91	53.85	2.78
100.	10.15	46.45	2.88	94.09	52.07	2.88
150.	15.69	43.82	2.63	124.42	50.15	2.63
200.	21.91	40.91	2.35	142.53	48.33	2.35
300.	33.79	35.44	1.98	165.84	44.51	1.98
500.	50.79	28.25	1.75	205.88	37.50	1.75
700.	61.59	24.67	1.76	252.68	32.62	1.76
1000.	74.11	22.12	1.88	334.72	28.41	1.88
1500.	95.34	20.28	2.00	478.61	25.33	2.00
2000.	120.94	19.26	2.00	605.11	24.07	2.00
3000.	185.67	17.63	1.79	780.17	23.13	1.79
5000.	345.37	14.38	1.31	936.05	22.78	1.31

We will now investigate the sensitivity of these parameters to typical electrical problems.

### Shorted Turn

A dipole with a 1 turn hard short will have the following properties:

Resistance: the coil dc resistance will be

$$R_{dc} (\text{shorted turn}) = \left(\frac{111}{112}\right) R_{dc}$$

since  $N = 112$  turns for a standard dipole

Inductance: the dc coil inductance will be

$$L (\text{shorted turn}) = \left(\frac{111}{112}\right)^2 L$$

The shorted turn will have the properties

$$\text{Resistance } R' \sim \frac{R_{oc}}{\frac{1}{12}} = .042 \Omega$$

$$\text{Inductance } L' \sim \frac{\mu_0}{4\pi} \left[ 1 + 4 \ln \frac{b}{a} \right] l$$

$$l = \text{length (m)} \sim 6.7 \text{ m}$$

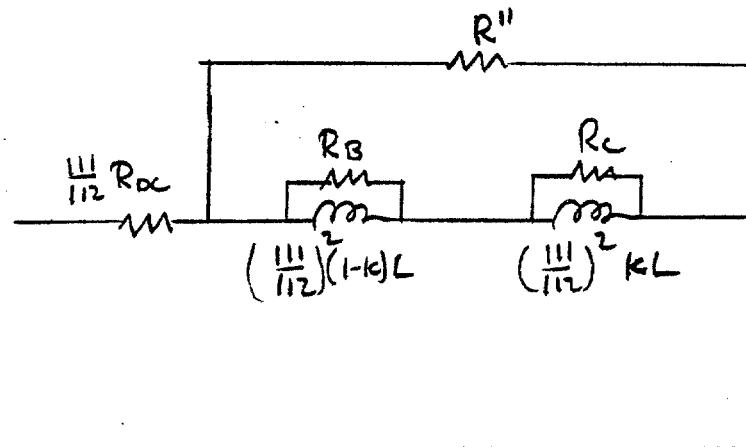
$$b = \text{separation of conductors (m)} \sim 15 \text{ cm}$$

$$a = \text{radius of conductors (m)} \sim .5 \text{ cm}$$

$$\therefore L' = .67 \left[ 1 + 4 \ln 30 \right] \mu \text{H} = 9.8 \mu \text{H}$$

$$\text{Mutual inductance: assume 100\%} \Rightarrow M^2 = LL'$$

Therefore our model now looks like



$$R'' = \frac{.042 \times (\frac{1}{12})^2 L}{9.8 \mu \text{H}}$$
$$= 206 \Omega$$

This model is analyzed as before, and we can now investigate the differences.

The inductance and Q changes are best seen at frequencies

$$F \gg \frac{1}{2\pi} \left( \frac{L}{R''} \right)^{-1} = \frac{1}{2\pi} \frac{206}{.049} = 700 \text{ Hz} \text{ as expected.}$$

(dipole with shorted turn)

F(Hz)	R <sub>s</sub>	L <sub>s</sub>	Q <sub>s</sub>	R <sub>p</sub>	L <sub>p</sub>	Q <sub>p</sub>
10.	4.86	48.07	0.62	6.74	172.42	0.62
15.	4.98	47.99	0.91	9.09	106.24	0.91
20.	5.16	47.88	1.17	12.18	83.06	1.17
30.	5.65	47.57	1.59	19.88	66.46	1.59
50.	7.18	46.61	2.04	37.05	57.82	2.04
70.	9.34	45.27	2.13	51.79	55.22	2.13
100.	13.45	42.70	1.99	66.97	53.44	1.99
150.	21.50	37.75	1.65	80.38	51.53	1.65
200.	29.58	32.86	1.40	87.23	49.72	1.40
300.	43.05	25.09	1.10	95.00	45.88	1.10
500.	60.33	16.74	0.87	106.15	38.77	0.87
700.	72.10	12.90	0.79	116.72	33.73	0.79
1000.	87.03	9.84	0.71	130.91	29.34	0.71
1500.	108.55	6.92	0.60	147.72	26.09	0.60
2000.	125.40	5.06	0.51	157.66	24.74	0.51
3000.	146.67	2.91	0.37	167.25	23.69	0.37
5000.	164.00	1.25	0.24	173.35	23.12	0.24

Note that L<sub>s</sub> shows a large decrease, while there is virtually no effect seen in L<sub>p</sub>. This is expected, as the parallel circuit model is expected to show the effect entirely in R<sub>p</sub> (and Q<sub>p</sub>).

It is also useful to note that as the resistance of a short increases, the frequency at which the effect can be seen also increases. In the above case the inductance change is only 12% at 100 Hz, but is 57% at 1 kHz. (for the series inductance model). In conclusion, to see a shorted turn, the series equivalent circuit model should be used, and frequencies in the 1 kHz range should be used.

### Comparison to Sharon Lackey Test

Sharon Lackey placed a 1 turn shorted loop inside the bore tube and noted the changes in L and Q. The properties of the loop were:

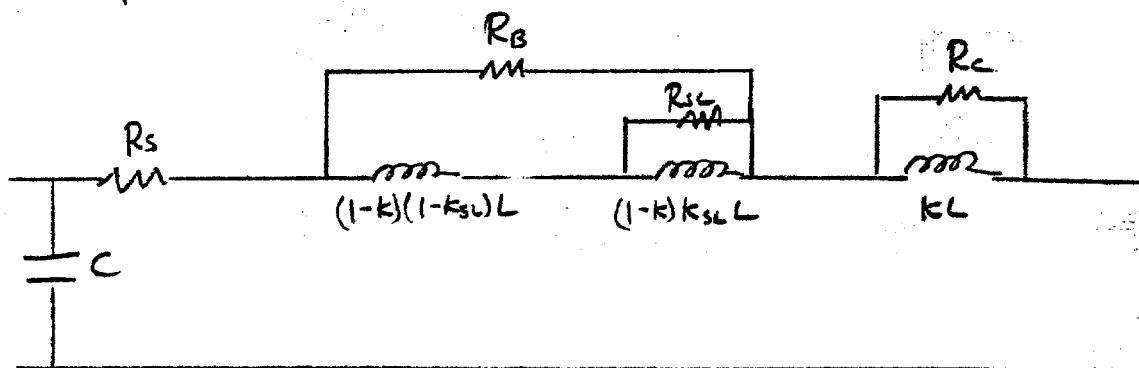
$$\text{Area} = 6.7 \text{ cm} \times 5 \text{ cm}$$

$$R = .093 \text{ ohms}$$

$$L \sim \frac{\mu_0}{4\pi} \left[ 1 + 4 \ln \frac{5 \text{ cm}}{.1 \text{ cm}} \right] 6.7 \sim 11 \mu \text{H}$$

$$\text{so } \tau \approx \frac{11 \mu \text{H}}{.093 \Omega} = 1.2 \times 10^{-4} \text{ sec}$$

We place such a loop inside the bore tube



$$R_{SL} \sim \frac{(1-k)k_{SL}L}{\pi} \text{ and } k_{SL} \sim 0.3$$

F(Hz)	R_s	L_s	Q_s	R_p	L_p	Q_p
10.	4.86	48.97	0.63	6.81	171.06	0.63
15.	4.94	48.94	0.93	9.25	104.97	0.93
20.	5.04	48.89	1.22	12.53	81.80	1.22
30.	5.34	48.75	1.72	21.16	65.20	1.72
50.	6.27	48.31	2.42	43.02	56.55	2.42
70.	7.63	47.68	2.75	65.24	54.00	2.75
100.	10.34	46.42	2.82	92.63	52.26	2.82
150.	16.10	43.77	2.56	121.79	50.44	2.56
200.	22.71	40.79	2.26	138.37	48.80	2.26
300.	35.37	35.22	1.88	159.99	45.21	1.88
500.	54.46	27.78	1.60	194.27	38.60	1.60
700.	68.62	23.58	1.51	225.15	33.96	1.51
1000.	85.14	20.35	1.50	277.22	29.38	1.50
1500.	109.76	17.64	1.51	361.58	25.33	1.51
2000.	132.40	15.73	1.49	427.54	22.79	1.49
3000.	181.76	13.85	1.44	556.66	20.56	1.44
5000.	284.12	11.24	1.24	723.29	18.52	1.24

Comparison of results	meas (PBALLS)		calc	
	$\Delta L$	$AQ$	$\Delta L$	$AQ$
120 Hz	0.5mH	.14	.05mH	.07
1kHz	1.5mH	.09	1.8mH	.38

So results are qualitatively in agreement.

Effects of Capacitance to beam tube, collars etc

The table below shows what happens when the capacitance in the model on pages 1 to 3 is increased to 30nF from 0.

F(Hz)	R <sub>s</sub>	L <sub>s</sub>	Q <sub>s</sub>	R <sub>P</sub>	L <sub>P</sub>	Q <sub>P</sub>
10.	4.86	48.97	0.63	6.81	171.06	0.63
15.	4.93	48.94	0.94	9.25	104.88	0.94
20.	5.03	48.89	1.22	12.53	81.70	1.22
30.	5.32	48.75	1.73	21.19	65.10	1.73
50.	6.23	48.32	2.44	43.23	56.46	2.44
70.	7.54	47.70	2.78	65.91	53.87	2.78
100.	10.16	46.47	2.87	94.09	52.10	2.87
150.	15.73	43.87	2.63	124.42	50.21	2.63
200.	21.99	40.97	2.34	142.53	48.44	2.34
300.	34.04	35.54	1.97	165.84	44.72	1.97
500.	51.64	28.41	1.73	205.88	37.92	1.73
700.	63.35	24.90	1.73	252.68	33.23	1.73
1000.	78.05	22.53	1.81	334.72	29.38	1.81
1500.	106.22	21.10	1.87	478.61	27.12	1.87
2000.	145.50	20.58	1.78	605.11	27.09	1.78
3000.	274.56	19.77	1.36	780.17	30.50	1.36
5000.	782.37	11.04	0.44	936.05	67.23	0.44

The most noticeable effects are at high frequencies, as expected. In essence, a pole of the form  $\frac{1}{1-\omega^2 LC}$  causes the imaginary part to increase (below  $\omega^2 = \frac{1}{LC}$ ). The inductance has risen from 22.12 to 22.53 mH at 1 kHz for example, with a small change in Q (decreased by .07). Sharon Lackey's measurements show similar magnitude

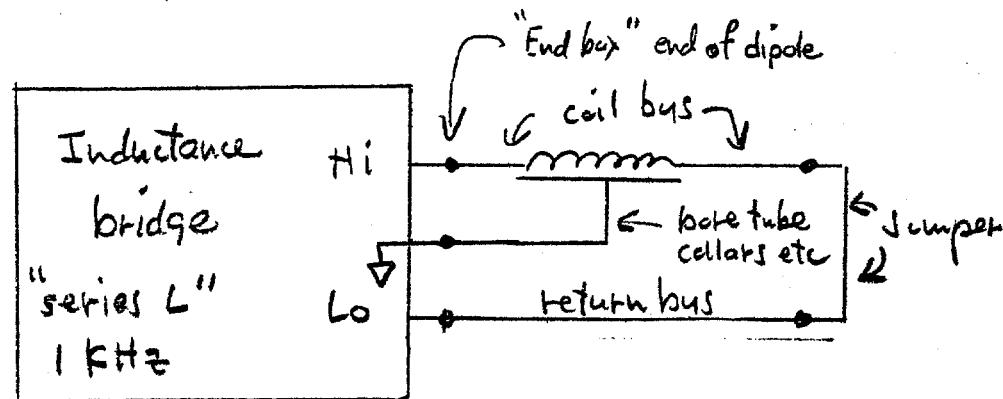
effects but of the opposite polarity when the bore tube and collars are grounded. In any case, the problems associated with stray capacitance occur at high frequencies and place an upper limit to the frequency at which L and Q measurements should be made (unless of course one wants to measure this effect)

### Conclusion

1. A series circuit equivalent model should be used for inductance bridge measurements
2. 1 kHz seems to be a good frequency
3. Due to the frequency dependence of  $L_s$  and Q, the frequency of the bridge oscillator should be maintained at  $1 \text{ kHz} \pm 0.5\%$  or so, so that measurements may be reproducible.
4. Due to the very low signal levels in certain inductance bridges (notably the HP 4261A) it should not be used, as the rather large size of EB dipoles makes them excellent antennas for picking up stray noise.
5. Use only inductance bridges which have one terminal grounded to which the metallic parts (bore tube, collars) may be attached. (this eliminates the HP 4261A). The HP 4260A seems to be adequate but not ideal

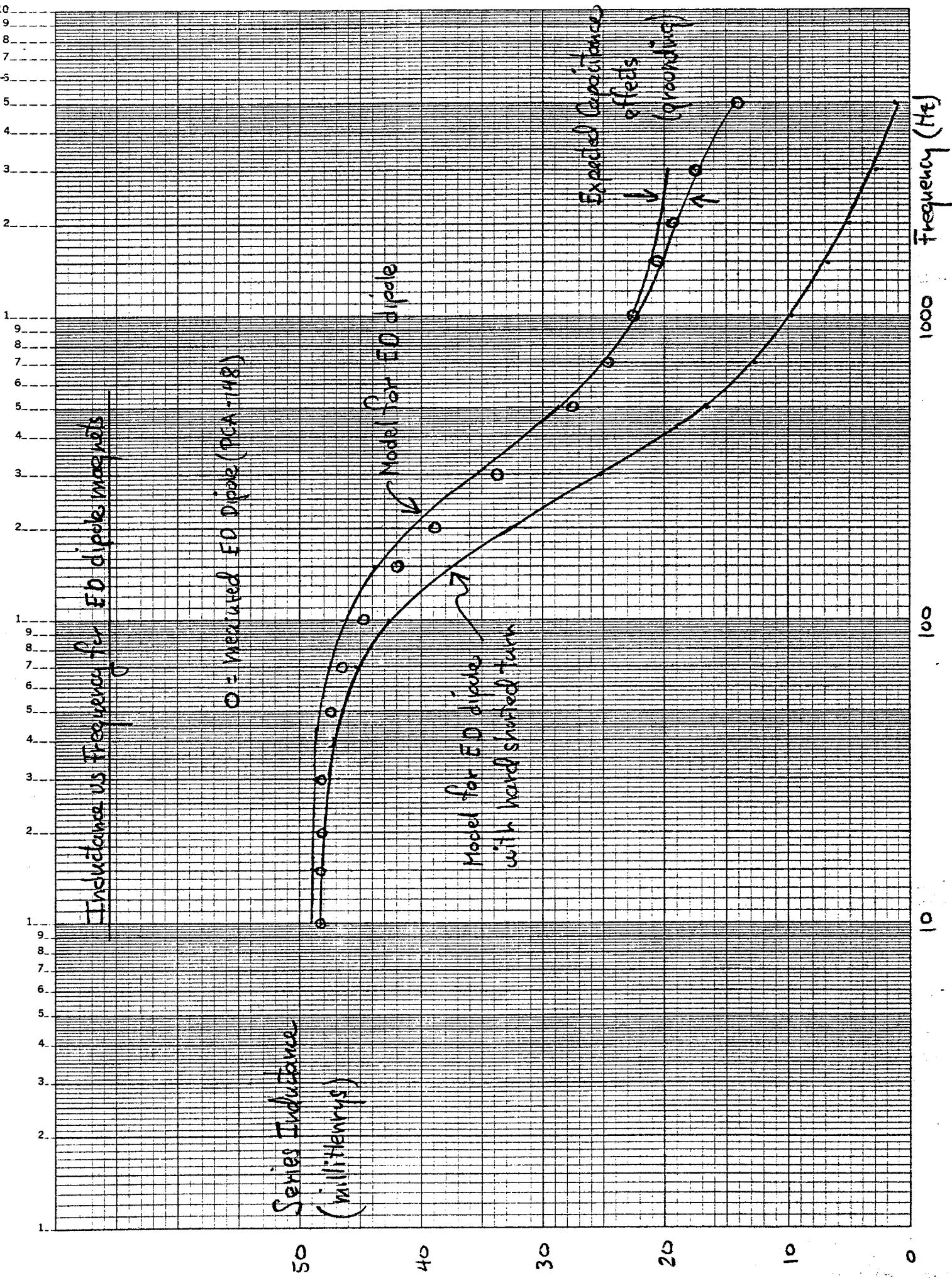
6. The inductance bridges should be certified to be within 1% on L and Q by A. Neubauer (Inst repair) for our range of measurements. (specifically,  $L = 20\text{mH}$ ,  $Q = 1-7$ )

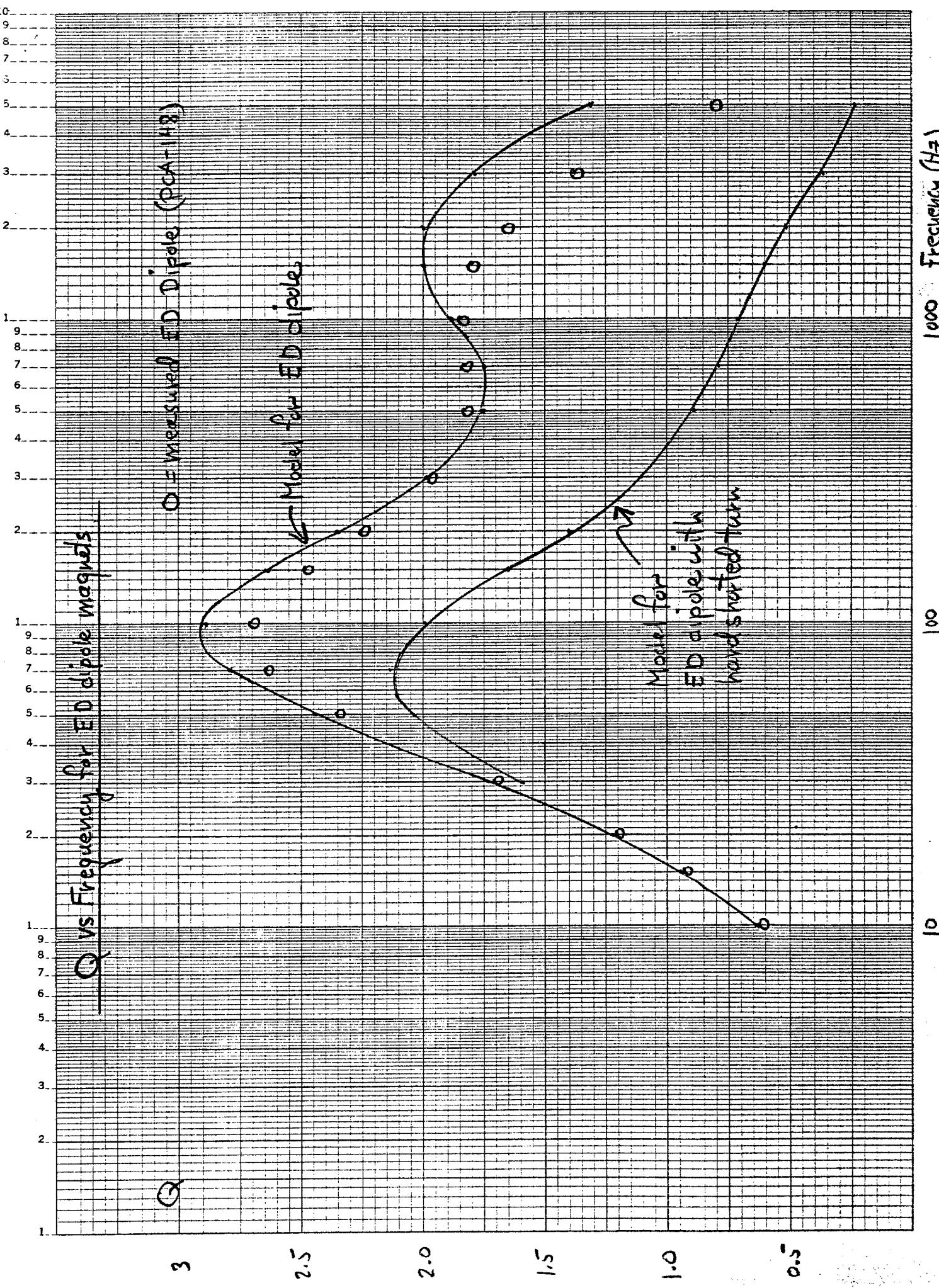
7. Always measure the dipole with the following configuration



8. The Magnet Factory should provide L and Q measurements in the above manner, measured after the test stand measurements are complete, and as the magnet is ready for shipment. Measurements made before the test stand measurements (B field, quench, AC Loss etc) are not adequate as test stand operation can modify certain characteristics. It is necessary that these measurements be made before shipment so that damage during transit can be detected if possible.

9. The Magnet Factory should also measure the DC resistance to (if possible)  $\pm 0.3\%$  and record the temperature (Resistance  $\propto$  Temp in  $^{\circ}\text{K}$ ), and the capacitance of the (coil + return bus) to (ground) (about  $60\text{nF}$ ).





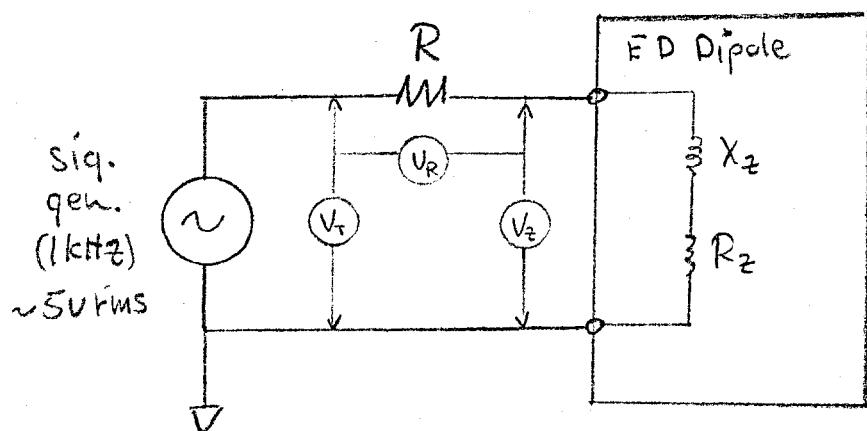
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## Proposal for Simple Reliable L and Q Measuring Circuit for ED Dipoles

the present inductance bridges available and in use suffer from the following problems:

1. Small signal level, making instrument sensitive to stray pickup.
2. Both terminals are floating, hence (severely) affected by grounding.
3. Complex circuit, hence easy to "lose" calibration.

I therefore propose that for any serious production line QC measurements that the following circuit be used:



$R$  is a precision resistor in the  $100\Omega$  to  $200\Omega$  range (non-inductive).

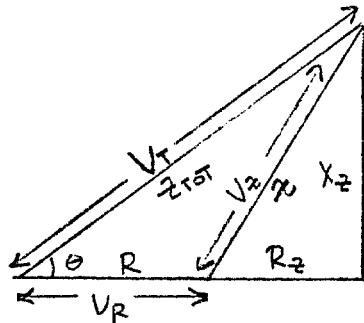
The 3 following voltages are measured (absolute voltages, no phase relationships):

$V_T$  = total voltage across  $R +$  dipole

$V_R$  = voltage across  $R$

$V_Z$  = voltage across dipole

A vector diagram of the voltages is:



$$\cos\theta = \frac{V_T^2 + V_R^2 - V_Z^2}{2 V_R V_T}$$

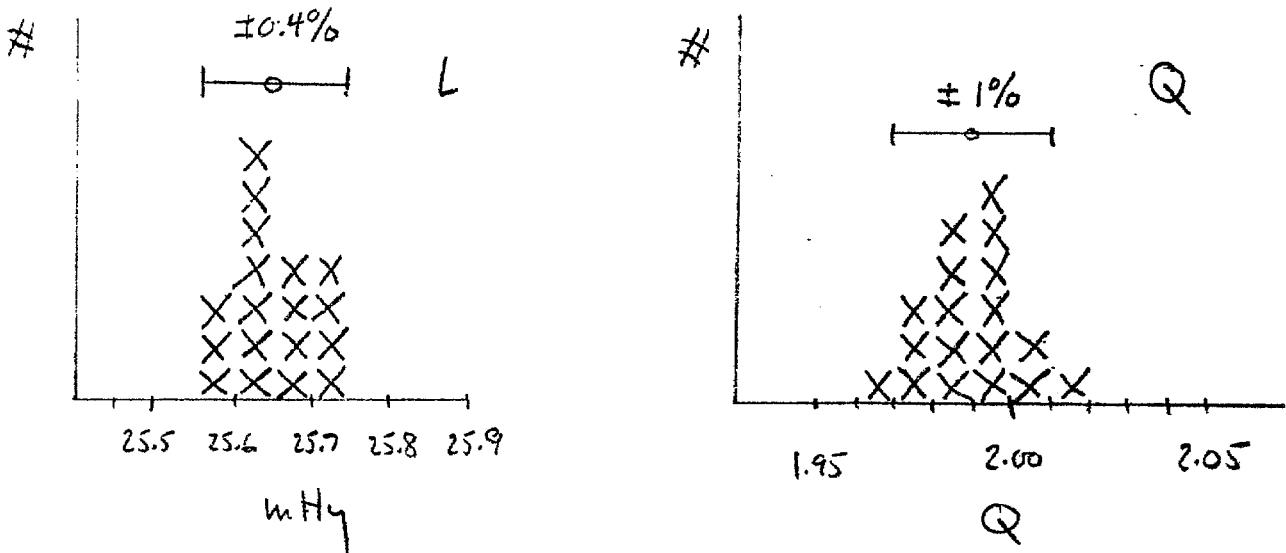
$$X_Z = Z_{TOT} \sin\theta = \frac{R V_T}{V_R} [1 - \cos^2\theta]^{1/2}$$

$$L_Z = \frac{X_Z \times 1000}{\omega} = \frac{1000 R V_T}{2\pi f V_R} [1 - \cos^2\theta]^{1/2} \text{ mHg.}$$

$$R_Z = Z_{TOT} \cos\theta - R = \frac{R V_T}{V_R} \cos\theta - R$$

$$Q = \frac{X_Z}{R_Z}$$

Typical precision of method can be seen from the following 18 measurements on a calibration standard provided to Jim Humbert on 2/20/79. the series resistor was varied from 100 to 200 ohms during measurement, and  $V_Z$  was varied from 35mV to 120mV. ( $f = 1 \text{ kHz}$ ).



So the precision is about  $\pm 0.5\%$  on  $L$  and  $\pm 1\%$  on  $Q$ .

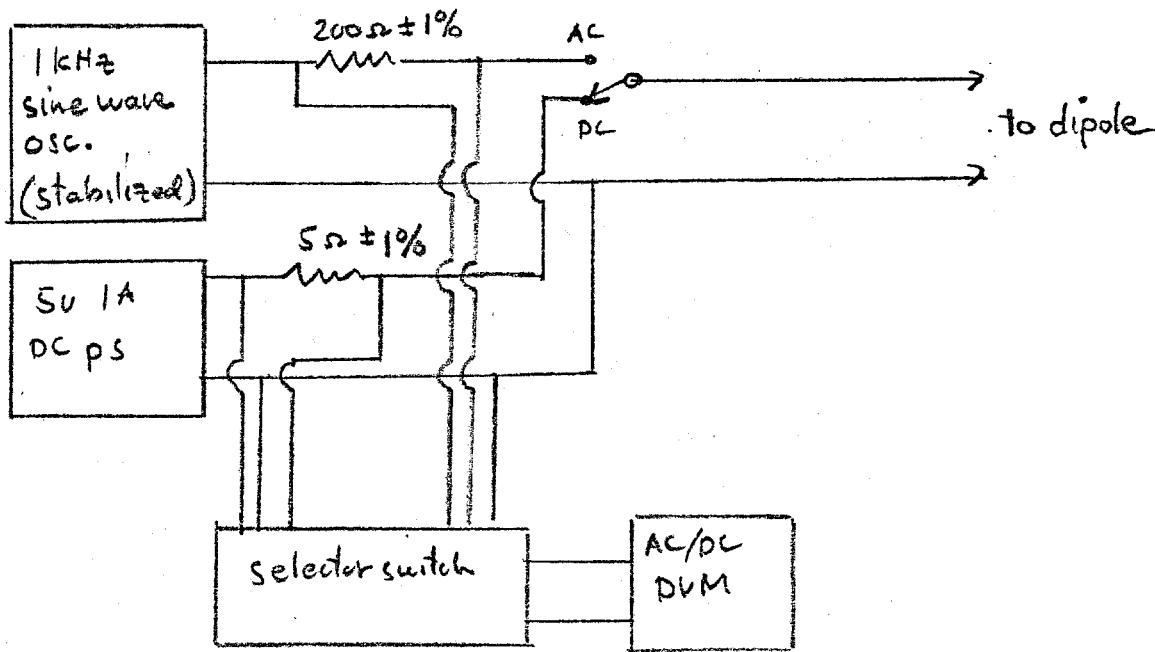
### Advantages of measuring technique

1. Inherently more accurate than bridge. Depends only on linearity of voltmeter, and stability of resistor. Inductance bridges are more elaborate, and have inherently poorer accuracy (typically  $\sim \pm 5\%$ ).
2. No knobs to adjust. Just 3 voltages to measure (or 2 voltage ratios)
3. One side of circuit may be grounded (not true of bridges)
4. Amplitude may be adjusted to overcome any inherent noise in industrial environment.

### Disadvantages

1. Requires use of algorithm to find  $L$  and  $Q$
2. Requires fabrication of ckt's (probably 2 or 3)

Actual proposed ckt (includes ckt for measuring DC resistance)



One option is to include precision rectifier ckt (active ckt) in selector switch so operator is not required to change DVM from AC to DC readings. Sine wave oscillator will probably require a hand-wound gapped core (I can supply materials). It needs to drive about 5 volts into a 200 ohm load (25mA rms) so can be done with op amp ckt.

If such ckts are built, they should be built either by an Accel Support Group or by Research Services Dept (Research Div).